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"The Design of Drive Systems for Vertical Lift." Michael F.Dlugosz,
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Disclaimer

THE DESIGN

OF

DRIVE SYSTEMS

FOR

VERTICAL LIFT BRIDGES

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1.0 INTRODUCTION

The Ohio Street Lift Bridge is located in the Industrial First Ward Area South of Downtown Buffalo. The bridge spans the Buffalo River approximately 2 miles east of Lake Erie.

The bridge has a trussed lift span of 270 feet which is abutted on each end by Lifting Towers. The Towers house the counterweights, lifting motors, machinery and miscellaneous maintenance and lifting apparatus. The towers are 153 feet in height and allow a navigational clearance of 100'-6" when the bridge is fully lifted.

This bridge was constructed in 1960 for the City of Buffalo's Department of Public Works at a cost of $5.6 million.

1.1 EXISTING SYSTEM

The span is currently operated by either of two identical adjustable voltage "Magamp Exciter" Systems. Each system employs one 100 HP direct current drive motor, an 85 KW motor generator set for DC drive power, a 3 KW motor-generator set for control power and a control panel. Leveling is accomplished by means of a "Static" skew correction system which maintains the skew within very close limits. A complete stand-by drive system exists in cases of emergency. Since the original installation, only minor repairs have been made to the existing electrical system.

Various problems exist with the current system. The existing power distribution system is approximately 30 years old and in need of significant repairs. Due to its age, spares for these electrical components are difficult, expensive and in some cases impossible to obtain. In addition, the electrical components, controlling the skew of the bridge, need to be replaced by a more accurate and reliable system.

After further analysis, by our Consultant, it was decided to update the existing electrical system. Variable Frequency Drives (VFD's) and Programmable Logic Control (PLC) were recommended as replacements for the existing D.C. drive systems and controls.

1.2 EXECUTIVE SUMMARY

The twin tower vertical lift bridge spanning the Buffalo River at Ohio Street in the City of Buffalo, was built in 1960. Normal and standby drive systems are located in each of the twin lifting towers. The existing drive system consists of 100 HP direct current (DC) drive motors, 85 KW motor-generator sets for DC drive power, 6.5 KW motor generator sets for control power and relay control panels.

A major rehabilitation or replacement of the existing drive system was needed because of age and condition. While, in the short term, rehabilitation was lower in cost than replacement, long term costs (i.e., maintenance) would be more expensive. Therefore, it was decided to replace the existing drive system using State-of-the-Art technology.

When confronted with the design (or redesign) of a drive system for a lift bridge, there are many factors which must be taken into consideration. Some of theses factors are: type of bridge, weather conditions, strength of prevailing wind, bridge weight, lift kinematics, reliability of power system, maintenance and operational considerations. In most situations, attention is focused on the specification of the drive components and the associated control systems. Much less attention is given to the kinematical and mechanical requirements. An effective design must integrate the kinematics and kinetics of the bridge being lifted with the components of the drive system and associated control systems. Such an integrated design was utilized when considering the redesign of the Ohio Street Bridge. First, the fundamental design criteria were developed based upon AASHTO Standards for Movable Highway Bridges and a basic sequence of operations was produced. Second, the kinematics and kinetics of the bridge were considered. The indicated parameters were then reflected through a series of existing drive components to establish parameters which an electrical drive and control system must produce. Then a variable frequency drive system and a PLC control system were developed to meet the indicated design parameters. Such an integrated system is currently under construction and scheduled for implementation in March 1991.

2.0 MECHANICAL ANALYSIS

Due to the fact that the power generation and control system were to be replaced and the mechanical components retained from the existing system, the mechanical analysis had a twofold objective:

- establish the motion (speed) and torque requirements at the motor position so that the power and control system could be appropriately designed.
- insure that the speed and torque reflected at each mechanical component was within existing capability. The capabilities of each of these components to withstand and emergency stop situation was also verified.

2.1 THE MOTION CYCLE

Since the mechanical components were to be retained in the renovated design a primary goal was to establish a motion cycle close to the existing (pre-renovation) cycle. The pre-renovation cycle consisted of increased motion from rest to peak speed in speed increments related to the vertical distance traversed. At each increment, the bridge was accelerated from one speed level to the next and then moved with uniform motion for a given distance. This sequence continued until peak speed was attained. A deceleration then brought the bridge to rest. A very slow motion was then used to bring the bridge to its final resting place. The described motion cycle is indicative of a lifting operation. A similar motion cycle exists for lowering. In the following only the lifting cycle will be described.

Specification of the pre-renovation motion cycle only included the speed increments used. The speed was increased from rest to full speed in increments of one-tenth full speed, one-quarter, one-half, three-quarters and finally, full speed. This general motion cycle is shown in Figure 2.1. No information was available as to the motion distances where change of speed (acceleration) or uniform motion (no acceleration) occurred. thus the motion distances had to be discerned. The bridge has a maximum travel of 86 feet. A typical motion cycle utilizes 82 feet off this travel. The first 79 feet are used to bring the bridge from rest to full speed and then to rest again. The remaining 3 feet of travel occurs at very slow speed. Only the first 79 feet of travel were considered in the analysis.

In order to develop quantitative values for the distances and speed indicated in Figure 2.1, the basic equations of rectilinear motion were employed. The change from one speed to the next was assumed to occur with a uniform acceleration. The equations which describe this motion are (see Section 5.0 Nomenclature for the definition of symbols used in equations):

$$v = a\ t + v_o \qquad \Rightarrow \qquad t = \frac{v - v_o}{a}$$

$$v^2 = v_o^2 = 2\ a\ s \qquad \Rightarrow \qquad a = \frac{v^2 - v_o^2}{2\ s}$$

The equations which describe the uniform motion are

$$a = 0$$

$$s = v\ t + s_o \qquad \Rightarrow \qquad t = \frac{s - s_o}{v}$$

To facilitate calculation, these equations were incorporated into a computer program. After some calculation iteration, the motion cycle shown in Figure 2.2 was accepted. The main features of this cycle are:

- the bridge was lifted from rest through peak speed in 73 feet and then decelerated to rest in six more feet attaining a total of 79 feet of travel,
- the total motion time was assumed to be 140 seconds,
- a speed change of one-quarter maximum speed is assumed to occur in 2 feet of travel,
- the maximum speed attained is 1.206 feet per second,
- the maximum uniform acceleration attained is .159 feet per second.

This maximum speed, when reflected through the mechanical drive components to the motor location, indicates a required motor shaft speed of 516 RPM. When reflected at each mechanical component, the speed was within the equipment capabilities. It should be noted a curve similar to Figure 2.1 was generated at the motor location.

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2.2 DYNAMIC PARAMETERS

With the motion cycle established, the dynamic (torque and horsepower) were predicted. The bridge platform supported by cable systems at the four corne cable systems pass over sheaves and are c[illegible]ec counterweight. The system is schematically shown [illegible] F The model shown in Figure 2.4 was considered at eac This model is seen to consist of two weights connected which passes over a pulley. The effects of friction b cable and pulley are included in the analysis. At ea the weights included are one-half the counterweight quarter the weight of the bridge platform. The weigh cables are neglected. A dynamic analysis was perform model to determine the torque required to produce t cycle described in Section 2.1. The peak torque, when through the mechanical drive components, indicates a mo torque of 523 foot pounds is required. Combined with shaft speed, a power of 55.3 horsepower must be generate the capability of each mechanical component to withst torque was verified.

2.3 WIND EFFECTS

The dynamic calculation described above was perform calm wind condition. Wind will add to the torque a requirements. Thus the analysis was also performed incl effects of a prevailing wind. A wind load of 20 po square foot of area exposed to a direction perpendicula longitudinal direction of the bridge was assumed. For motion cycle, the torque and power increase by about [illegible]0 The values required including wind effects are 627 [illegible]o and 61.6 horsepower.

2.4 EMERGENCY STOP

During a lifting or lowering operation it may be ne to stop the bridge due to some emergency. In this situat bridge is traveling at some velocity when all the bra suddenly applied. The acceleration that occurs for an braking torque is determined in addition to the dista bridge will move under this braking action and the time i it moves. In this analysis, the maximum tooth load counterweight sheave gear is used to limit the torque that applied to the system. It is found that if all the t brakes are applied, a sufficient torque could be gener equal or surpass the maximum tooth load. Thus the emergen situation is analyzed for the case that the thrustor bra apply an effective torque at the counterweight sheave g 10,000 foot-pounds. For both the lifting and lowering cas distance and time in which the bridge will stop in situations are evaluated. This motion can be accomplis adjusting the inner (motor) thrustor brake to a capacity foot-pounds and the outer thrustor brake to a capacity foot-pounds.

3.0 ELECTRICAL ANALYSIS

The electrical analysis included a thorough survey, equipment evaluation, and design of new drive and control systems coordinated with the mechanical operating machinery. The objective of the analysis was:

- to define the load requirements and select the optimum motor and drive parameters for specification;
- to define the feedback and performance criteria for the control system specification;
- to select the parameters for proper integration of the existing operating machinery, drive system, and control system.

3.1 THE EXISTING SYSTEM

The existing power distribution serving the bridge is approximately 30 years old and in need of significant replacement of equipment. The present electrical service consists of two separate 480 volt services from the Niagara Mohawk Power Corporation Vault. A manual transfer switch can be operated to select the incoming power feed. The power distribution equipment and control relays are located at the basement electrical room.

The bridge has two separate and independent drive systems, which can be powered from either services. The normal and emergency drive systems each consist of one lift subsystem in each tower machine room. Each lifting subsystem includes a 100 HP direct current (DC) drive motor, an 85 KW shunt wound DC generator combined with a 125 HP AC squirrel cage induction motor (MG set) for drive power, and a 6.5 KW MG set for control power.

3.2 EQUIPMENT EVALUATION

A survey of the existing drive components, control system, and inspection of the machinery was performed which included disassembly of components and visual inspection by millwrights and machinists. The operating machinery inspection indicated that the mechanical components were in good condition and selective refurbishment of brakes, gearboxes, clutches, and cable connection work was required.

The existing power distribution system was completely replaced and two services of greater capacity were incorporated into the design. The new power distribution system included a selectively coordinated protection scheme with an automatic transfer switch for increased reliability.

The existing electrical drive components had performed well for approximately 30 years of service, although the increased maintenance, availability of spare parts, and reliability had become important factors for consideration. New Variable Frequency Drives (VFD) and AC Squirrel Cage Induction Motors, together with a Programmable Logic Controller (PLC), were recommended as replacement for the original DC drive system and Westinghouse Control System. A simplified block diagram of the existing system is shown in Figure 3.2, while the new system block diagram is shown in Figure 3.1. The PLC interfaces with the new operator control panel and controls the operating sequence and the VFD's. The PLC communicates with the remote I/O racks located at the machine rooms and it monitors both position and speed of the bridge and auxiliary functions.

3.3 DEFINITION OF THE LOAD

The type of load and characteristics of the load are important considerations for the proper application of a drive system. The mechanical analysis and the original speed-torque curves by Westinghouse identified the speed torque requirements (nominal) as follows:

Peak Shaft Speed:	516 RPM
Full Load Torque:	523 FT-LB
Maximum Motor HP:	55.3

With wind effects taken into consideration:

Full Load Torque:	627 FT-LB
Maximum Motor HP:	61.6

These parameters are associated with the bridge motion cycle shown in Figure 2.1.

3.4 MOTOR SELECTION

The mechanical analysis and the original speed torque curves identified the drive motor output horsepower and continuous torque requirements over the entire speed range, including the starting torque requirements.

The original span drive motors were rated as follows:

> 100 HP, 1/2 Hour, 75 Degrees C Rise, 230 Volt, 525 RPM, Straight Shunt Totally Enclosed Non-ventilated DC Mill Motor. This motor develops a full load torque of 1000 FT-LB at 525 RPM.

The type of motor and motor parameters were determined based upon compliance with the performance criteria and other design considerations. The AC Squirrel Cage Induction Motor represents a simple construction, reliable, least expensive, readily available, and easy to maintain product in comparison with DC motors, wound rotor, and synchronous motors. The AC NEMA Class B Design Squirrel Cage Induction Motor has been effectively combined with the appropriate VFD for applications where the load characteristics, speed range, and drive requirements permit optimum drive performance. Motor selection criteria matched to load requirements include the following:

- Frame Size
- Full Load Speed
- Torque Ratings
  - Full Load Torque
  - Locked Rotor Torque
  - Breakdown Torque
- Enclosure and Ventilation System
- Insulation System and Temperature Rise
- Service Factor
- Time Ratings
- Locked Rotor KVA (NEMA)

The new span drive motors were rated as follows:

L507 Frame Size, 60 Hz, 600 RPM, NEMA Design B AC Squirrel Cage Induction Motors, TEFC, SF=1.15.

Full Load Torque:	1000 FT-LB
Locked Rotor Torque:	115% Full Load
Breakdown Torque:	200% Full Load

Class F Insulation System with Class B temperature rise, with continuous time rating.

3.5 VFD SELECTION

The load definition and motor parameters were coordinated with the selection of the VFD performance criteria. The output rating of the VFD was sized to provide sufficient amps for motor full load conditions, plus additional derating factors for other conditions. We have selected a breakaway torque range between 120% and 150% of full load torque to satisfy the requirement for sufficient starting torque to accelerate the bridge from rest. The pulse width modulated type VFD high waveform quality has torque and current directly proportional between 100 - 150% Full Load Torque, and was selected.

The acceleration requirements and the acceleration time considerations were incorporated into the VFD specification. The acceleration torque derived from the mechanical analysis was compared to the VFD capability to avoid tripping the VFD current limit or accell time adjustment setpoint. The accell time adjustments are coordinated with the mechanical analysis to satisfy the load conditions and acceleration ramps shown in Figure 2.1, which reduce shock and wear on the machinery components.

The motor overload and overtemperature protection ranges were determined based upon the expected short time overload conditions. Adjustable motor overload protection and motor thermal switches are incorporated into the drive specification for enhanced protection.

The VFD controller output ratings and input ratings are coordinated with downstream drive requirements and upstream power distribution system components.

3.6 CONTROL SYSTEM SELECTION

A Programmable Logic Controller (PLC) was selected to replace the existing Westinghouse relay controls for the bridge. The PLC afforded a higher degree of reliability, diagnostics capability, flexibility for parameter adjustment, better response time and drive feedback resolution. In addition, the PLC increased the set of control functions to include: Counters, Timers, Data Transfers, Arithmetic Functions, Priority I/O Functions, and direct communications over a high speed data link from each VFD to the PLC.

The existing position feedback system for the bridge utilized rotary selsyns and heavy duty limit switches. The heavy duty limit switches were replaced and are utilized for redundant position feedback; the new optical encoders interfaced to the PLC provide the primary position feedback system. The critical task of monitoring skew between the North and South Towers is achieved by PLC comparison of position registers during bridge motion. Software limits in parallel with hardwired limit switches provide additional operating safety.

The new Operator Console is designed to be similar in appearance to the original, with new functions incorporated. Automatic raise and lower sequences and maintenance functions have been included to supplement the manual controls, while the operator maintains direct supervisory control over all motion.

The basic configuration of the VFD and PLC system was designed with performance specifications to assure that high quality components were utilized in this critical application. In addition, the specific role of the system's integrator and local support capability were important factors in the design. Prior experience with combining VFD's and PLC's for similar applications, programming capability, and availability/depth of local, qualified, support personnel were identified in the specifications.

The specific parameters for drive integration were identified, including encoder resolution, type of communications interface and speed, type and quantity of PLC I/O hardware, parameters for VFD velocity loop, and other considerations.

4.0 SUMMARY

In summary, the careful evaluation of the existing facilities and equipment, together with a coordinated analysis effort between mechanical and electrical disciplines, should result in many more operating years for this movable bridge.

5.0 NOMENCLATURE

TERM	DEFINITION
a	UNIFORM ACCELERATION
v	SPEED
v_o	SPEED AT SOME INITIAL INTERVAL POINT
s	DISTANCE
s_o	DISTANCE AT SOME INITIAL INTERVAL POINT
t	TIME

6.0 FIGURES

The figures referenced in this report are contained in this section. These figures are presented in the order of reference.

GENERAL BRIDGE MOTION CYCLE

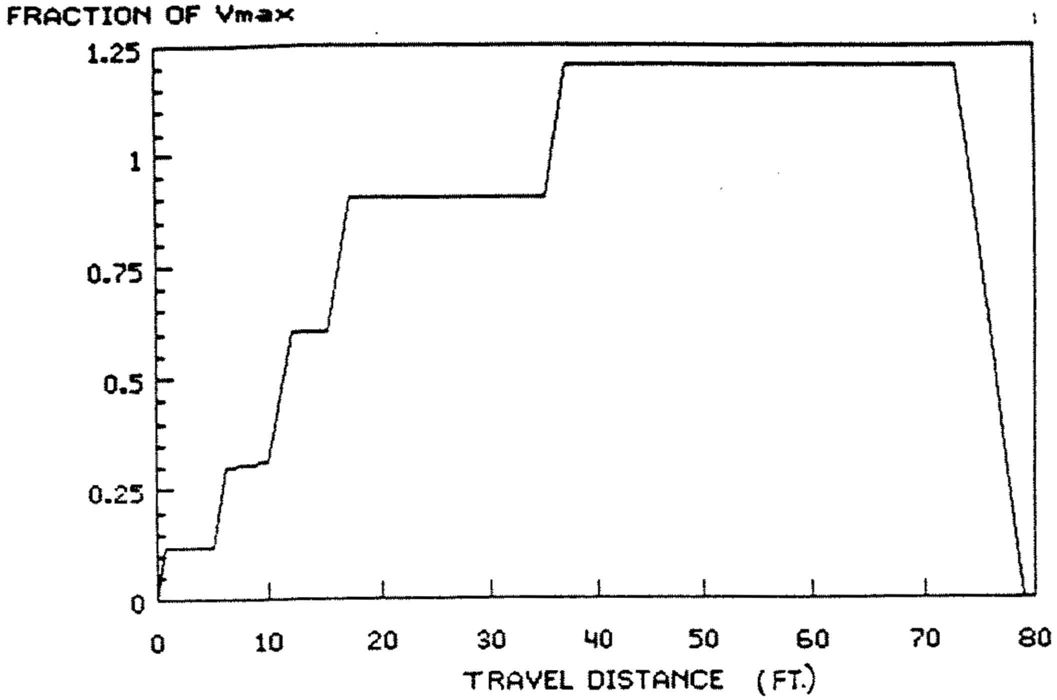

Figure 2.1

BRIDGE MOTION CYCLE

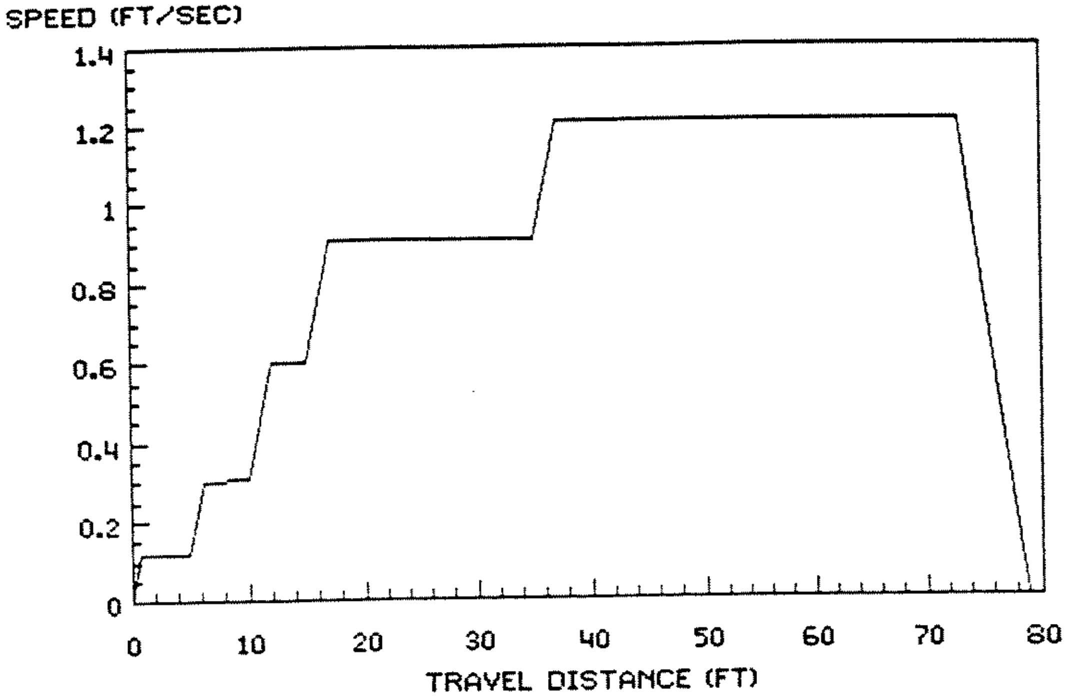

Figure 2.2

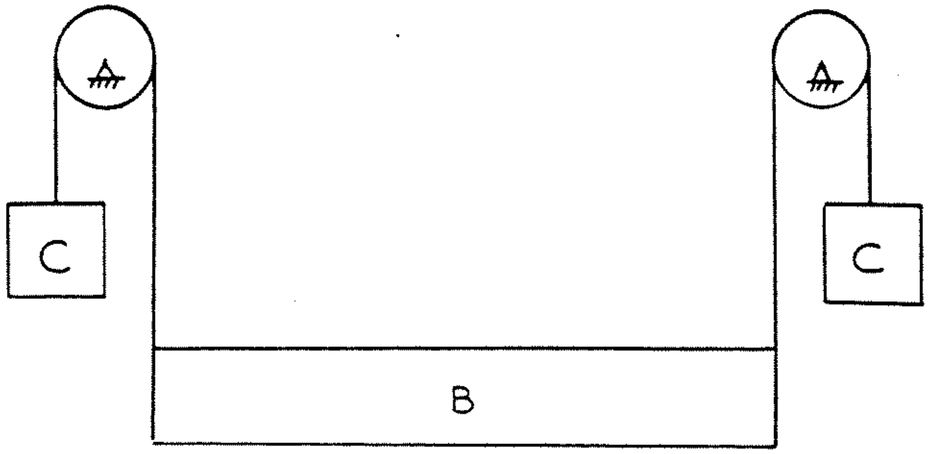

FIGURE 2.3 BRIDGE SCHEMATIC

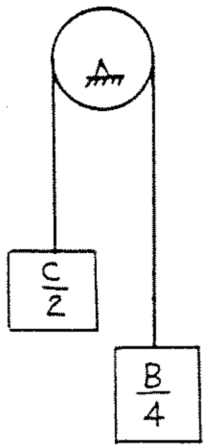

FIGURE 2.4 ANALYSIS MODEL

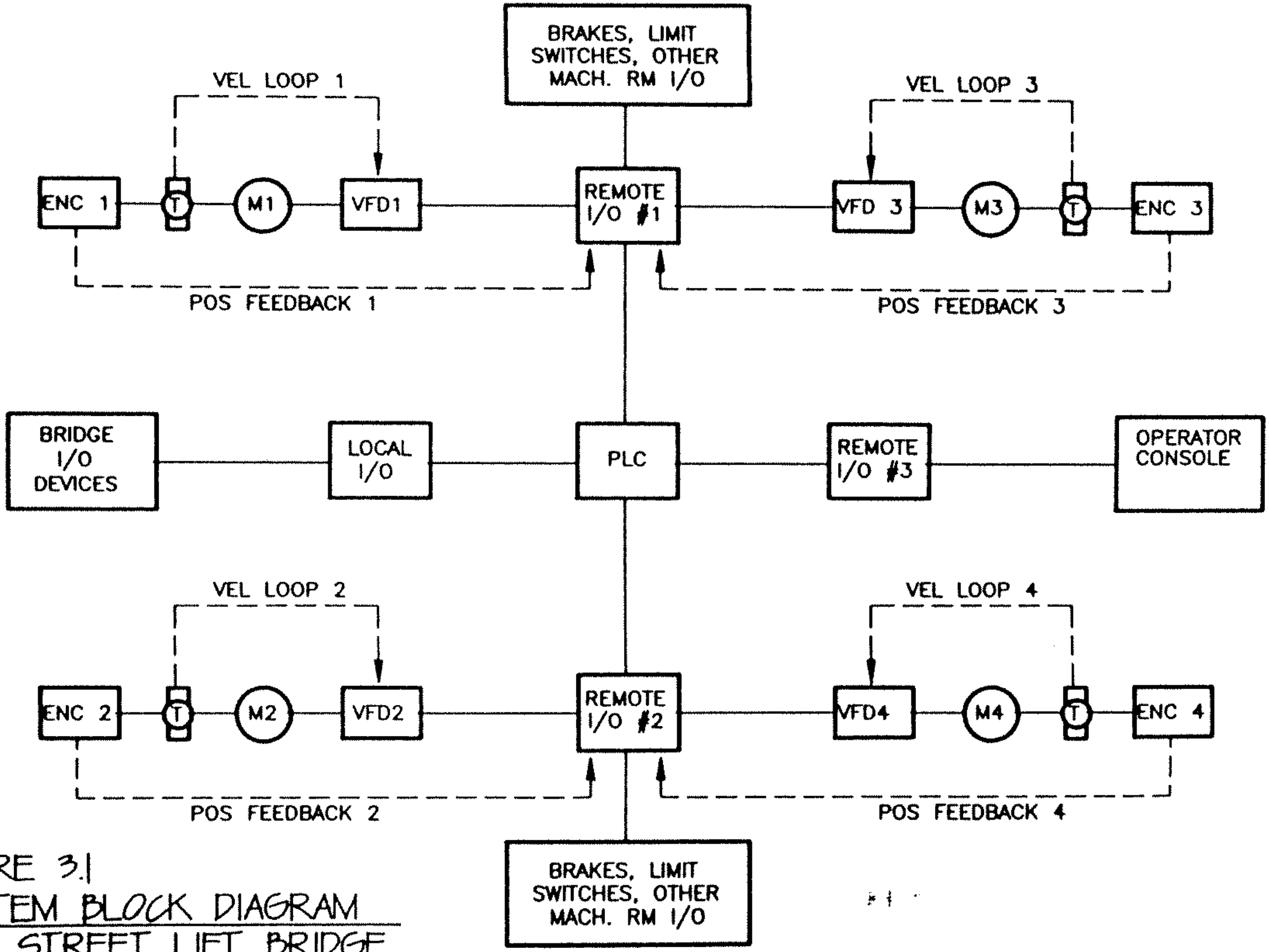

FIGURE 3.1
SYSTEM BLOCK DIAGRAM
OHIO STREET LIFT BRIDGE

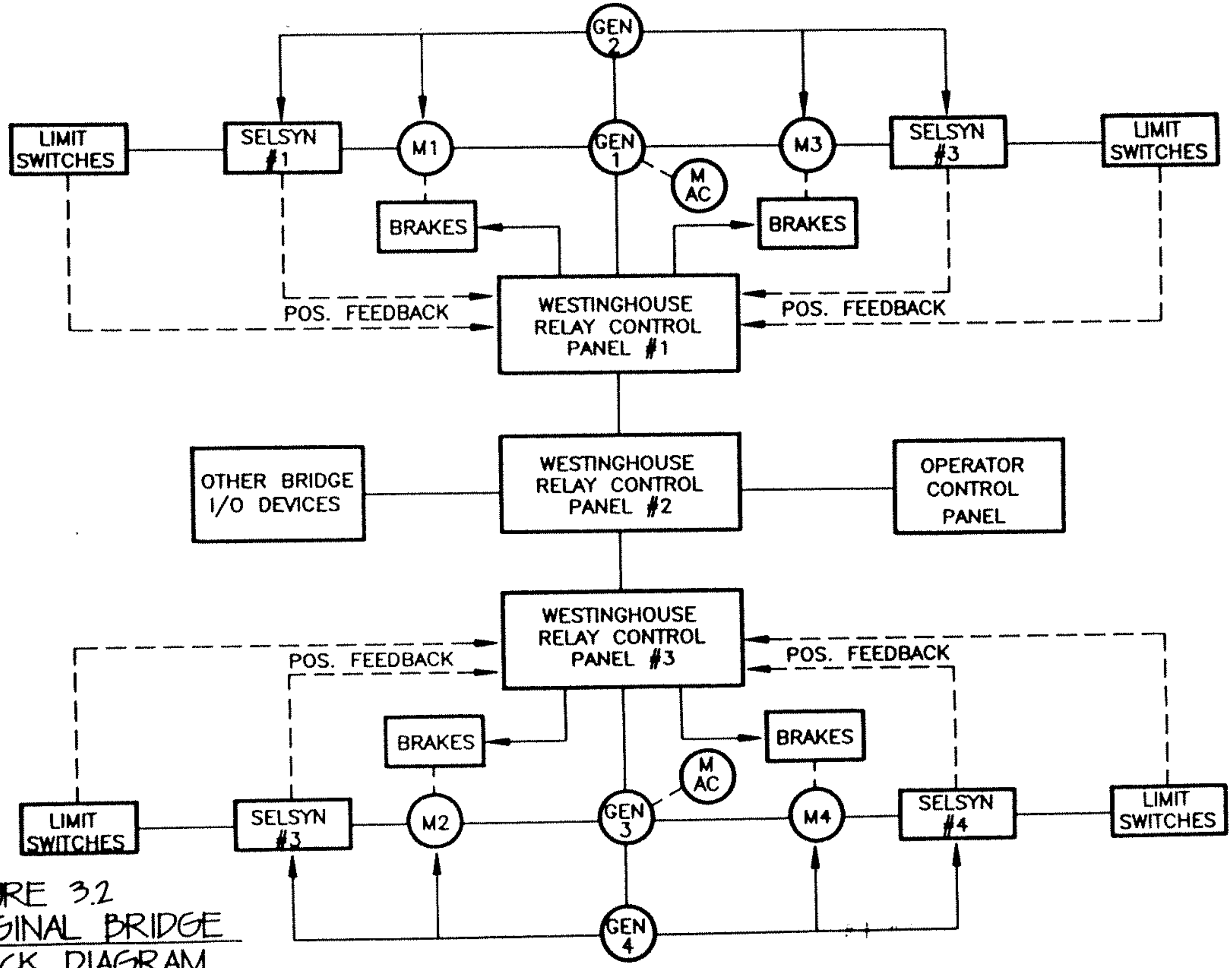

FIGURE 3.2
ORIGINAL BRIDGE
BLOCK DIAGRAM